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LINKING R&D TO PROBLEMS EXPERIENCED IN SOLIDS  
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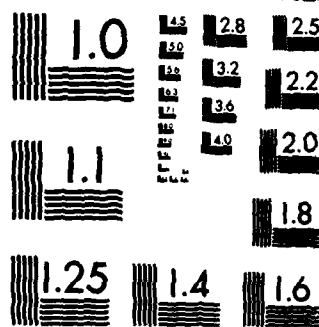
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LINKING R&D TO PROBLEMS EXPERIENCED IN SOLIDS PROCESSING

Edward W. Merrow

November 1984

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## INTRODUCTION

This paper reports the results of a 24-month Rand project that attempted to establish empirically the appropriate priorities for funding R&D for solids processing.<sup>1</sup> The research was funded by the U.S. Department of Energy and by The Rand Corporation's Private Sector Sponsors Program, an agenda of research for the oil and chemical industries.

This project grew out of a prior finding that plants which process solids anywhere on the main process train perform more poorly than plants that process only liquids and gases.<sup>2</sup> This poor performance quite clearly costs the U.S. economy in general, and the process industries in particular, billions of dollars in lost revenue. Poor solids processing plant performance also threatens the economic viability of synthetic fuels and a number of other energy processes based on solids processing technology. Moreover, the earlier work found that plants built recently generally performed no better than those built in the mid to late 1960's. This finding suggested the possibility that the real problems underlying poor performance were not being resolved by the industry's R&D programs.

Industrial R&D is, of course, but one part of a larger system that translates improvements and breakthroughs in science into commercial products. Figure 1 displays this research, development, and commercialization process in a simplified way. Government often plays an important role in shaping the basic research agenda at universities through the type of research it funds (and declines to fund). The scientific community provides much of the raw material for applied

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<sup>1</sup>The detailed research report upon which this paper is partially based will be available in February, 1985. At that time, it can be obtained from the Publications Department, The Rand Corporation, 1700 Main Street, Santa Monica, CA. 90406. It should be referenced as R-3216. The views expressed in this paper are those of the author. They are not intended to in any way represent the views of The Rand Corporation or the sponsors of the research on which this paper is based.

<sup>2</sup>See E.W. Merrow, K.E. Phillips, and C.W. Myers, *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants*, Santa Monica, CA.: The Rand Corporation, 1981; Section V: Plant Performance.

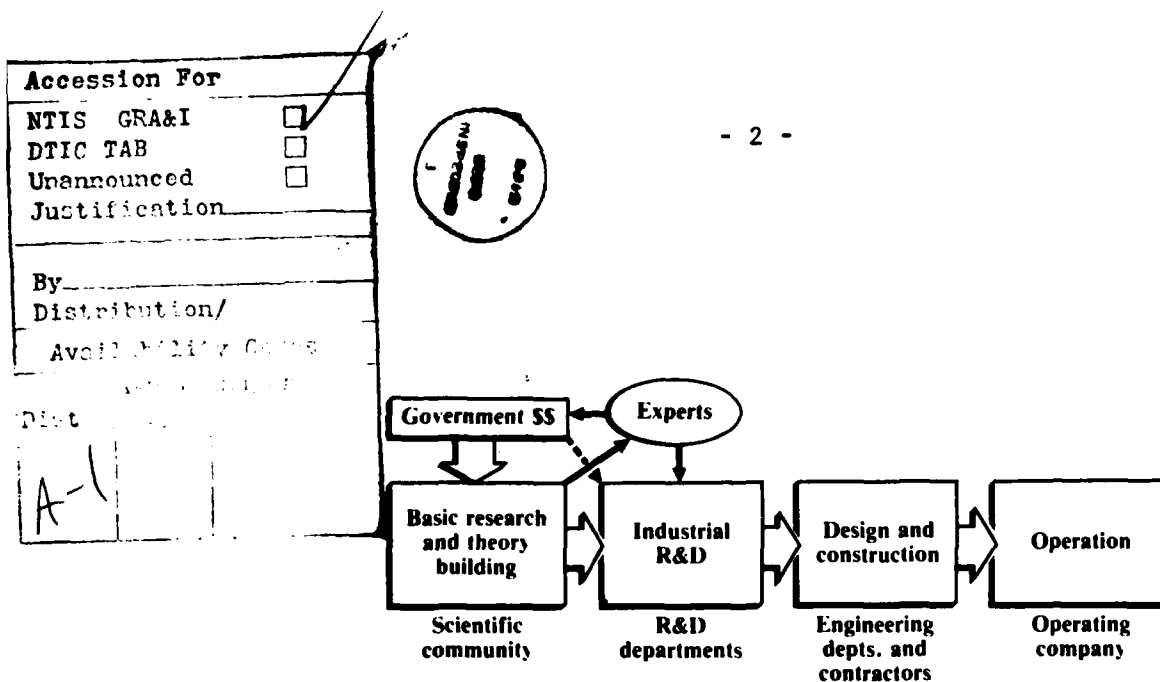


Fig. 1 -- The Research, Development, and Commercialization Process

industrial R&D via improvements in scientific knowledge. In addition, the fate of new processes, process improvements and new products depends on much beyond R&D: the quality and ingenuity of design and construction, the skill of the operators, and finally, the all-important marketplace.

Rather than attempt to examine all aspects of this process, we addressed the efficiency of this system by linking empirically R&D programs that preceded a commercial process with how well that commercial process worked in an actual plant setting. Because of our earlier finding, we focused on plant performance--that is, how well the plants worked after start-up as a percent of design--as our basic figure of merit. Because plant performance is such a driver of plant economics, we felt that this provided us a way of linking the characteristics of an R&D program to the profitability of the resulting commercial process. We developed a database of some 37 solids processing projects in order to address the following questions:

- What are the key problem areas?
- Are there systematic blind spots in the industry's approach to allocating R&D for these facilities, at least for this type of facility?
- If so, why have such blind spots persisted?

To preview the conclusions of the study briefly:

- The key performance problems in solids processing plants are associated with mechanical and physical difficulties rather than problems associated with process chemistry.
- The problems that are not successfully resolved are those that do not fit well with the way in which the oil and chemical industries have evolved their R&D system; that is, these are problems that tend not to be well integrated into the paradigm that goes from improvements in basic knowledge of chemistry to improved processes and products in the market place.
- Because the real problems don't fit with the R&D paradigm, industry has tended to neglect the areas, and government R&D expenditures have tended to reflect rather than complement directions chosen by the industry.
- The solids processing industry needs not only to change the priorities of its R&D agenda but also to consider fundamental changes in the ways in which R&D allocations are made and the R&D system operates.

The paper is divided into five sections. The second section explains the nature of the problem of allocating funds for R&D projects. The third section explains our approach to the problem, an approach that focused on R&D in the solids processing industries. The fourth section explains the actual quantitative linking of R&D and plant performance which was the basis of our statistical approach. The fifth and final section suggests how the setting of R&D priorities might be improved and offers some views about the strengths and weaknesses of the industrial R&D system in the oil and chemical industries.

## THE R&D ALLOCATION PROBLEM

R&D allocation is the principal problem faced by R&D managers and by those responsible for setting policy about R&D. Why is allocating R&D so difficult? The primary reason is that R&D, like all searches for information, contains inherent uncertainties. When searching for information, one cannot be sure that the results of the search will be fruitful or even that, if they are fruitful, the results will have been worth the cost. In practice this means that measuring the value of an R&D project is difficult and establishing a clear relationship between R&D and profitability (or some other figure of merit) is more difficult still.

It is possible to link the level of R&D funding and the profitability of an industry or even the growth in an entire economy. This has been done many times generally with the conclusion that a relationship exists between increased R&D expenditure and increased profitability in an industry and more rapid growth in national economies. However, because systematic data are hard to develop, a link between an individual R&D project and profits is generally difficult to establish, even retrospectively.

So where can the R&D manager turn for guidance on strategic R&D allocation as well as guidance for individual project selection? Each firm tends to develop its own peculiar approach to R&D allocation, but most approaches are ultimately based in one way or another on expert judgment and opinion. Unfortunately, the use of expert opinion does little to resolve the R&D allocation problem because it cannot address in a systematic way the relationship between R&D allocations and the ultimate goals of R&D: profits (in the case of the private sector) or social benefits of some sort (in the case of government).

The most systematic use of expert opinion is the formal expert panel: a group of scientists, chosen on the basis of their prominence in research to provide guidance and advice to both individual firms and the government. However, the use of experts, even in highly formalized and rigorous ways, is problematic for several reasons. First, the conclusions reached are inherently subjective. Second, the results necessarily reflect the composition of the panel. One can hardly blame



the set of experts for failing to come up with avenues of research that go far outside those that made them experts in the first place. Third, the results of expert panels generally lack any clear set of priorities. This reflects, in part, a fourth problem: the fact that the results are not clearly tied to some desirable outcome such as profitability, lower plant cost, or better plant performance.

## **R&D AND PLANT PERFORMANCE IN THE SOLIDS PROCESSING INDUSTRIES**

The goal of our analysis was to link statistically the nature of the R&D that was performed--measured by how much work went in and by the types of problems that were addressed--with the performance of the plants as measured by how well they worked relative to design and by the types of specific process and equipment failures that occurred.

The universe of plants that we are examining here includes any process plant, that is, a plant that involves a molecular change to the feed material in which there is some solids processing on the main process train. This would include plants that process liquids and gases to solid material as well as those that start with either refined or raw solid feedstocks and process them either to liquids, gases, or solids as products.

A few examples will clarify these distinctions. Plants that use liquid and gas feedstock and create solids downstream include petroleum coking, polyethylene, and plastics plants. Examples of the use of refined solid feedstocks would include petroleum coke calcining, the manufacture of many explosives and the manufacture of many herbicides. Raw solid feedstock plants are those that involve the use of a mineral taken directly from the ground and sent to a processing facility. This includes virtually all synthetic fuels processing, hydrometallurgical facilities, and all other manufacture of chemicals from unrefined minerals.

We specifically exclude from our analysis plants that have only solid catalysts rather than solids as feeds, intermediate products, or final products. We also exclude plants that involve only physical operations--such as coal-crushing facilities--because they do not meet our criterion of molecular change. And we exclude solids processing facilities for which solids are an incidental by-product. For example,

a refinery, the process of removing  $H_2S$  will generally end with elemental sulphur and some water. However, it is surely not useful to call it a solids processing facility.

### The Solids Processing R&D Programs in the Database

The data for the R&D programs and the commercial processing plants that resulted were provided by some 25 companies in the oil, chemical and minerals industries covering plants built between 1963 and 1983. A database totaling 37 projects and plants was assembled over a two and a half year period. All of the plants were built in the United States and Canada. We deliberately included a wide variety of systems involving a large number of different solids processes.

As Figure 2 suggests, our database also includes a wide variety of R&D programs. All, however, are highly applied efforts: they do not attempt to break new scientific ground, although in some cases they do attempt to introduce radically new chemical processes. The vast majority of these programs aimed to introduce cost reducing processes as opposed to new products. The average cost of these programs, in terms of professional staff, is about \$5 million dollars but they range up to

| <ul style="list-style-type: none"> <li>• All are highly applied programs</li> <li>• Average cost \$5MM with range to \$25MM</li> <li>• Companies assess R&amp;D programs on 0 to 5 scales in following areas:</li> </ul> |   |
|--|---|
| Chemistry Issues   | Physical/Mechanical Issues  |
| <ul style="list-style-type: none"> <li>— Temperature limits and control</li> <li>— Pressure limits and control</li> <li>— Impurity buildup in process streams</li> <li>— Corrosion/erosion</li> </ul>                    | <ul style="list-style-type: none"> <li>— Feedstock characterization</li> <li>— Abrasion</li> <li>— Solids handling</li> <li>— Liquids handling</li> <li>— Waste handling</li> </ul> |

Fig. 2 -- Industrial R&D Programs in the Database

about \$25 million in today's dollars. (These figures do not include any of the costs associated with the development facilities that accompanied the R&D process, such as bench scale pilot plants, integrated pilots and the like, which in general cost many times the professional salaries involved.)

Among the data we requested from companies was their assessment of the R&D efforts for the particular plant they were providing to the database. Their responses covered a large number of R&D areas with the degree of difficulty measured on a zero to 5 scale plus qualitative discussion. Under the rubric of chemistry-related issues are such classic problems of temperature/pressure limits and control, impurity buildup in intermediate process streams, and corrosion and erosion difficulties. Under the rubric of physics/mechanical problems are those associated with characterizing feedstocks, abrasion and various materials handling issues, especially for solids, liquids, and waste streams. The resulting data provided us with a fairly comprehensive view of the R&D performed, the nature of the key problem areas, and the extent to which new problem areas were identified at various stages.

### **Plant Performance**

Our database also allowed us to address in detail the issue of how well the plants actually worked. Figure 3 shows that some of the plants worked reasonably well, that is, at 80 percent of design or better. However, about two-thirds of the plants operated at less than 80 percent of design at the end of the first year, and a third of the sample were operating at less than 60 percent of design. The average plant was at 64 percent. The fact that 90 to 95 percent constitutes the industry standard provides some insight into how disappointing the performance of these solids processing units is.

Figure 3 also illustrates an even more dramatic and distressing picture when we differentiate those plants with solid feedstocks of any sort from those that had only liquids and gases as feedstocks with solids being created downstream. Now the average performance drops to under 50 percent of design and only a small portion of the plants could be considered to have operated reasonably well. The enlarged database,

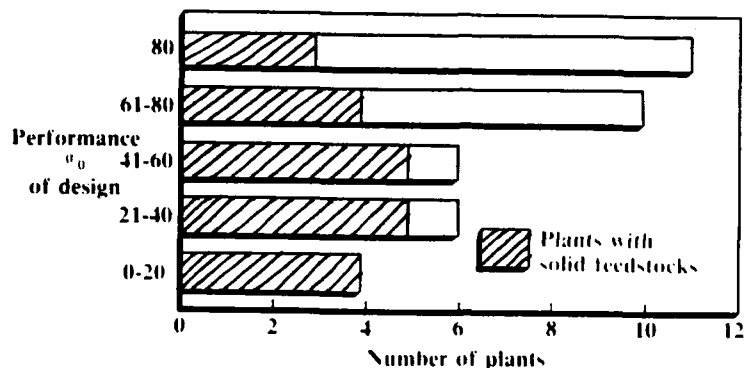


Fig. 3 -- How Well Did the Plants Perform?

then, confirms our earlier finding that solids processing plants generally perform poorly. In the next section we discuss how we actually went about analyzing this problem based upon the data that we developed.

#### LINKING R&D AND PLANT PERFORMANCE

In this section of the paper, we will summarize the analysis that permitted us to tie R&D efforts to results for the solids processing plants in the database. First, we will present the "best fit" regression model for plant production as a percent of design after a period for startup. We will then explore the relationship between R&D issues tackled for the plants and the most important variable in predicting plant performance: the knowledge basis for setting the heat and material balances for the commercial plant.

Figure 4 shows the relationship between the performance of plants and their key characteristics. There are three primary drivers of plant performance:

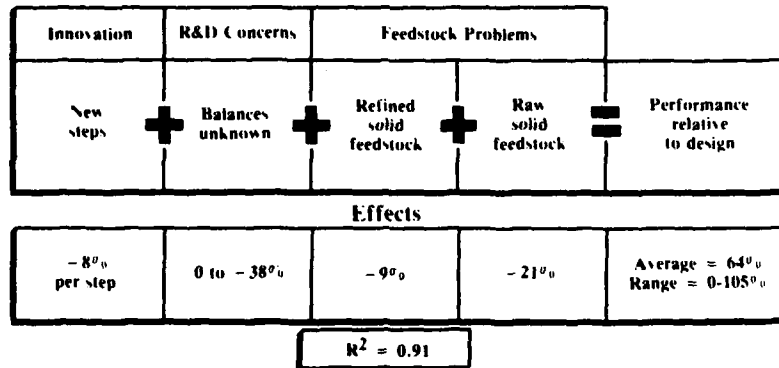


Fig. 4 -- Understanding Plant Performance

- the extent to which the plant is innovative,
- the extent to which there are problems with solid feedstocks, and
- the extent to which the heat and material balances are based upon data from prior commercial units or have to be calculated from experimental data, analogous plants, pilot plants or theory for a given plant. The portion of the heat and material balances around major process blocks not based on data from prior commercial plants, we call the "balances unknown."

#### Innovation and Plant Performance

Figure 5 shows the relationship between how well plants perform and the best measure of the degree of innovativeness: number of process steps incorporated in a plant that have no history of commercial use. The pattern is clear. The plants in the database with three or more new steps tended to work very poorly and those with no new steps, on average, worked reasonably well. If we simply take the number of new steps into account, it accounts for about 60 percent of the variation in plant performance.

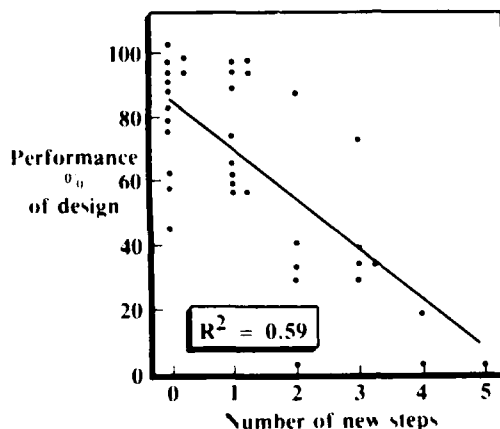


Fig. 5 -- Performance is Related to New Steps

### Type of Feedstock and Plant Performance

Figure 6 shows the relationship between the type of feedstock that a plant employs and how well it works. Starting with the simplest type of feedstocks--that is, gases and liquids--the average performance is close to 90 percent and the poorest of the plants operates at about 60 percent of design. As soon as we move to solid feedstocks, however, the situation changes radically. The average plant that employs a refined solid feedstock only works at about 50 percent of design, and the range of plant performance varies from zero percent--a plant that did not work at all--to about 90 percent. As we move to raw solid feedstocks--that is, feedstocks that are minerals that have not been previously processed--the performance of those plants drops to about 40 percent of design, with the range from zero to one at 80 percent.

### H&M Balances and Plant Performance

As most readers of this paper are aware, the heat and material balances for a process plant are the basic equations describing heat and mass input and output from every step in the plant. The heat and material balances establish the sizing of all equipment throughout the

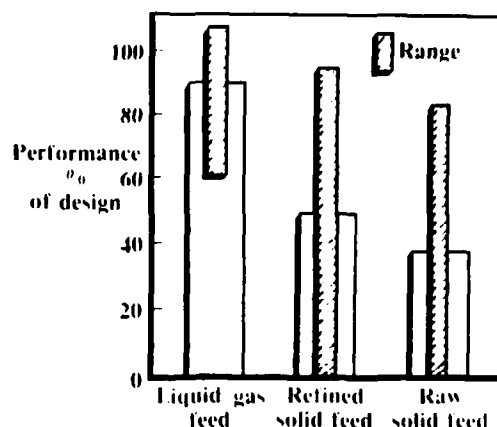


Fig. 6 -- Performance is Related to Type of Feedstock

plant. Without H&M balances one really does not have a process. The development of the H&M balances requires a combination of data and mechanical and chemical theory and, as ever, there is a tradeoff between the two: the better the theory, the less pressing the need for data and vice versa.

In this study we examined the relationship between the source of the H&M data employed and the resulting commercial plant operating performance. Figure 7 shows the result by plotting the relationship between what was known about the heat and material balances based on actual operating experience from prior plants and how well the plants worked. There is a very strong, almost overwhelming, relationship between the knowledge of the heat and material balances and good plant performance. Even the poorest of those plants in which all of the heat and material balances were based on data from prior commercial units operated at about 70 percent of design with the best operating at about 105 percent of design. We see precisely the opposite when none of the heat and material balances are based on commercial experience. In that case plant performance ranges from zero percent only up to about 60 percent.

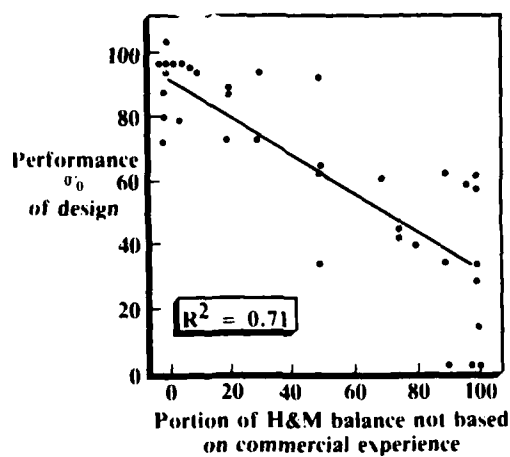


Fig. 7 -- H&M Balances Drive Performance

This single variable, the knowledge basis for the heat and material balances, accounts for some 71 percent of the variation in plant performance among plants in our database. And of all the variables that predict plant performance, the heat and material balances have the largest possible effect. If one knows none of the heat and material balances from prior units, the plant performance is about 38 percent of design less than what one would otherwise expect.<sup>3</sup>

We have established that the knowledge of heat and materials balances is the most important determinant of plant performance. We can also show that the knowledge of heat and material balances can be directly and systematically linked to the nature of the R&D problems that occurred. Figure 8 summarizes the relationships. Recall that we have divided R&D problems that were actually encountered in the programs

<sup>3</sup>We have found that in terms of the relationship between the knowledge basis for the H&M equations and plant performance, the only distinction that really counts is whether or not the basis is a prior commercial unit. The extent to which test facilities, such as pilot plants, were used does not improve the explanation of plant performance. This does not mean, by the way, that pilots are unnecessary; it means only that they do not appear to resolve the sort of problems reflected by the knowledge of the heat and material balances.



| • Chemistry       | Balances | Performance |
|-------------------|----------|-------------|
| Temperature       |          |             |
| Pressure          |          |             |
| Impurity          |          |             |
| Corrosion/erosion |          |             |
| • Physics         |          |             |
| Feed character    |          |             |
| Abrasion          |          |             |
| Solids handling   |          |             |
| Liquids handling  |          |             |
| Waste handling    |          |             |

Not correlated    
  Correlated    
  Strongly correlated

Fig. 8 -- How R&D Problems Are Related to H&M Balances

that preceded the commercial plants into two broad categories: those related to chemistry and those related to physical and mechanical problems. The pattern of relationship between the heat and material balances on the one hand and the chemistry-related problems on the other, is weak at best. There is no relationship between temperature and pressure issues and heat and material balances; and that is also reflected in the fact that there is no relationship between those items and plant performance. There is some relationship between impurities in intermediate process streams and the heat and material balances. That, however, is largely an artifact of the relationship between corrosion and erosion in plants and process stream impurities. Process stream impurities sometimes result from the erosion and corrosion of the vessels and pipes. The only element in the chemistry-related items that is clearly related to the balance equations and to plant performance is corrosion/erosion (erosion being the interactive effect of corrosion and abrasion).

A different pattern appears in the physics-related items, those having to do with characterizing the feedstock, abrasion, and materials handling. A very stark pattern of relationship exists between those

items and what is known about the heat and material balances and in turn how well the plants perform. When the problems that besiege a plant's development are related to physics, these problems are being manifest by the fact that the heat and materials balances are not well understood, and that, in turn, is being manifest in poor plant performance.

Figure 9 summarizes the way in which we statistically link performance problems for commercial plants to R&D problems that were identified and worked on in R&D but were apparently not resolved. First, solid feedstocks in and of themselves can be shown to affect performance poorly. However, when one has solid feedstocks the probability that the heat and material balances will be known declines, other things being equal. The other major drivers of performance are R&D problems associated with handling solid materials and wastes as they affect what is understood about the heat and material balances. These areas therefore provide very large potential payoffs for R&D.

Figure 10 summarizes the relationship between the heat and material balances and R&D problems. It shows the statistical relationship between what one knows about the heat and material balances and the

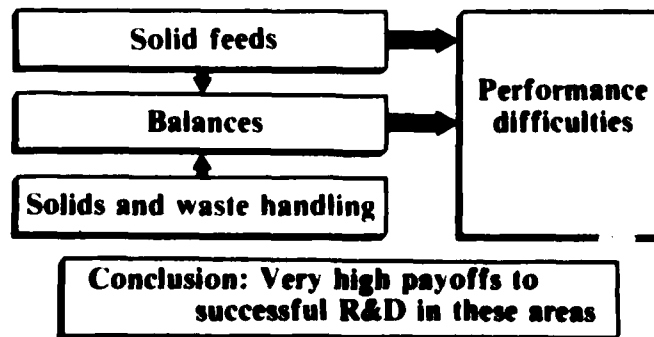


Fig. 9 -- Tracing Sources of Performance Failure to R&D Issues

| R&D Problems                       |   | Type of Feed                      |                       |
|------------------------------------|---|-----------------------------------|-----------------------|
| Degree of solids handling problems | + | Degree of waste handling problems | +                     |
|                                    |   | Use of solid feed                 | =                     |
|                                    |   |                                   | % H&M balances known  |
| Effects                            |   |                                   |                       |
| -0 to -50%                         |   | -36%                              | Average 52%<br>0-100% |
| Number of new steps has no effect  |   | $R^2 = 0.73$                      |                       |

Fig. 10 -- Understanding the Balance Equations

extent to which there are difficulties with handling solids, handling wastes, and the existence of solid feedstocks. R&D problems associated with solids handling have the largest potential effect: a reduction of up to 50 percent of what is known about the heat and material balances. Recall that this relationship is not causal but associative; that is, when one does not know the heat and material balances, one will have difficulties with solids handling and vice-versa. Second, the degree of difficulty handling waste is associated with poor knowledge of the heat and material balances up to a maximum relationship of about 30 percent. And finally, when one employs a solid feedstock, one reduces what is known about the heat and material balances on average by about a third relative to liquid and gas feedstock facilities. These three variables account for nearly three quarters of the variation in what is known about heat and material balances.

Table 1 documents the depth of the problems encountered by the 37 plants we examined and groups them in ways which illustrate the significance of the variables we have identified. Two items are of particular note. First, only 6 percent of the plants in the sample experienced no major performance problems. A major performance problem

Table 1

MECHANICAL PROBLEMS DOMINATE PLANT FAILURES

|  | <u>Percent<br/>of Sample</u> |
|--|------------------------------|
| Plants with "major" performance problems | 94                           |
| Related to H&M balances:                 |                              |
| • Solids transfer failures               | 52                           |
| • Mis-sizing of process blocks           | 19                           |
| Solids and waste handling:               |                              |
| • Failure of mechanical equipment        | 48                           |
| • Plugging of reactor by solids          | 45                           |
| • Fines and dust                         | 23                           |
| Chemistry related problems:              |                              |
| • Corrosion/erosion                      | 29                           |
| • Other failures from process chemistry  | 6                            |

is defined as one that was responsible for complete shut-down of the plant for one week or more. Second, the overwhelming majority of the problems reported are related to the physics and mechanics of the processes rather than to the chemistry. For example, over one half of the plants experienced failures in transferring solids from one place to another and nearly half experienced failure of mechanical equipment and physical plugging of reactors by solids. The only chemistry-related problems of any note were related to corrosion and erosion, those chemistry-related problems that border chemistry and physics.

#### IMPLICATIONS FOR R&D PRIORITIES AND STRATEGIES

We turn now to the implications of our analysis for refashioning R&D priorities for solids processing and then more generally to the issue of how well the industrial R&D system is working in the process industries.

The R&D priorities suggested by our analysis are quite clear:

1. **Solids behavior in processing.** A great deal more basic research needs to be done on solids behavior in chemical processing. Specifically, work on solids flow and solids handling and on waste handling and waste production would be useful.
2. **Feedstock-related problems.** Applied research on feedstock-related problems is also clearly needed. Processing solid feedstocks has an enormous effect on plant performance -- independent of any other characteristic of the technology. In part this effect manifests the theoretical poverty of solids processing. However, it is also a problem related to inadequate equipment and inadequate understanding of equipment requirements.
3. **Corrosion and erosion.** The only chemistry-related area in which additional research would appear to be warranted is for corrosion and erosion-related problems.

These programs would take years to bear major fruit, but the industry can take stopgap measures to improve its experience with solids processing facilities. Additional equipment testing would undoubtedly ameliorate, though not resolve, the problems associated with much solids processing. This equipment testing would involve feeding the actual materials as used in the new plant, with the vendor's equipment that is proposed for the solids processing. One would then get a much better indication of whether or not a particular equipment item would actually perform the service for which it was being proposed. Of course, such testing does not allow solids processing to make use of the generalizable designs that are characteristic of liquid and gas processing and that have been very instrumental in effectuating major advances in the processing of liquids and gases. That generalizability can only result from an improved theoretical knowledge of solids behavior.

Figure 11 shows how successful R&D along the lines we have proposed could reduce the product cost. On the horizontal axis we have increasing performance as a percent of design. We take as our base case performance at 90 percent of design as being equated with a product cost of 100 percent. The most dramatic improvements in product cost are associated with better understanding of the processing of solids feedstocks and improvement in fundamental knowledge of the heat and material balances.

We are left with the basic question of why such chronically poor performance of solids processing plants has persisted at least over the last fifteen years or so for which we have data. Why haven't additional resources been allocated to the fundamental work on the processing of solids material--that is, to achieving a better understanding of how to set heat and material balances when solids are involved--as well as on specific items such as solids handling?

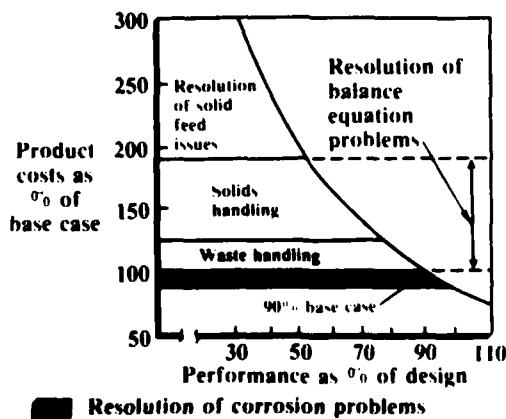


Fig. 11 -- Implications for R&D Priorities

We believe that the situation has not improved because of basic communication problems in the solids processing industries. Figure 12 illustrates these problems.

- Academic science does not appear to be pursuing the basic research that is needed because there is no clear demand--that is, funding--for that research. There is no funding because the expert panels drawn from the scientific community to help establish priorities for R&D allocations fail to identify problem areas outside their chemistry-related realms of expertise.
- Within the industry itself, the problems that are most germane to plant performance are not solved but passed along the process from industrial R&D to engineering and from engineering to operations. In talking to industrial R&D departments in the oil and chemical industries, we detected a peculiar attitude toward R&D outside the area of chemistry: the feeling that such research is not within the mainstream, indeed, not worthy

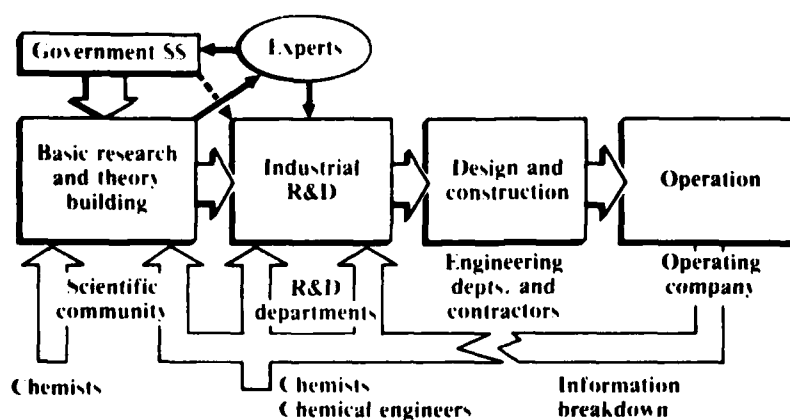


Fig. 12 -- Why Doesn't the Situation Improve

of serious concern. R&D managers in the oil and chemical industries appear to feel that mechanical problems should be the province of the design engineering departments, and perhaps even plant managers, and not a subject for industrial R&D.

- Unfortunately, however, engineering departments, and particularly the design teams for process plants, tend to be dominated by chemical engineers who also see physics and mechanics-related issues as outside their area of expertise. They then have the attitude that such mechanical problems can be fixed in start-up--that is, by the operators.
- But in operations the problems are not being solved but only patched. And no solutions are forthcoming because there is no effective feedback from plant operators back to the industrial R&D departments and from there to the research community. If the information is in fact getting through--and we believe that it is not--it is not being heeded. It is striking to see the predominance of mechanical and physical failures and yet the continued emphasis on chemistry-related rather than physics-related R&D by industrial departments.

Based upon this research and our view of the process industries over the last half a dozen years or so, we can see an industry that is extremely effective in translating advances in chemistry into commercial technology and products. However, that system that works so well in chemistry-related areas appears to break down almost immediately and at all levels when the problems are outside the chemistry paradigm.

These problems suggest that different ways of setting the R&D agenda for both the scientific and industrial R&D are badly needed. They also suggest that as the oil and chemical industries attempt to move outside their traditional area to increased use of biotechnology, they may run directly into the inflexibility of the industrial R&D system. For the same reason, the national goal of cost-effective synthetic fuels may prove to be elusive, not because sufficient R&D is lacking, but because the basic problems that affect synthetic fuels are those that are receiving least attention.



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